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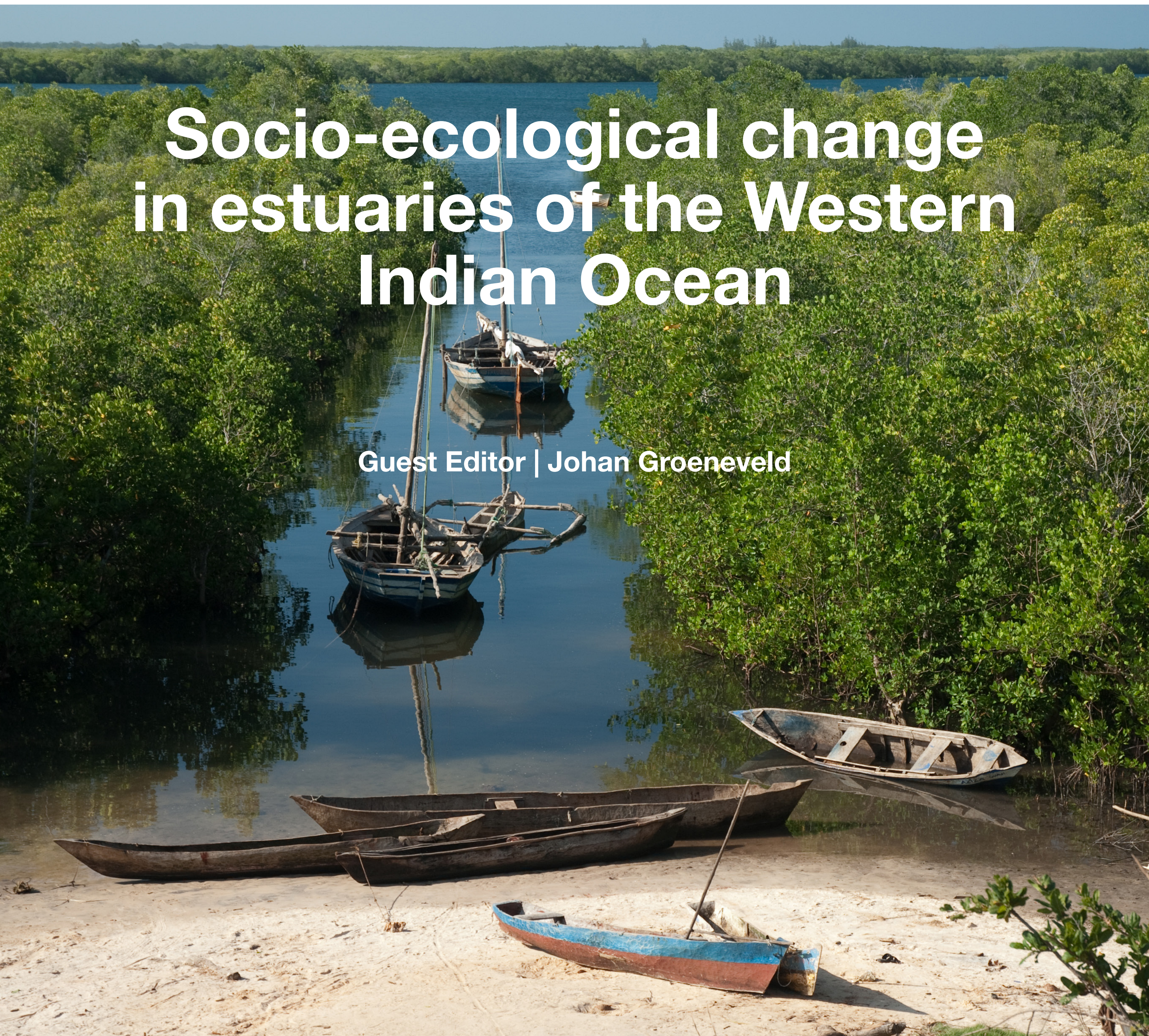

Socio-ecological change in estuaries of the Western Indian Ocean

Guest Editor | Johan Groeneveld

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Cover image: The Rovuma Estuary creeks near Quionga in Mozambique. © José Paula, 2007

Socio-ecological change in the Ruvu Estuary in Tanzania, inferred from land-use and land-cover (LULC) analysis and estuarine fisheries

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Abstract

Ecosystem goods and services derived from estuaries have sustained coastal livelihoods in the Western Indian Ocean (WIO) region throughout recorded history. Estuaries provide fertile and seasonally irrigated space for planting crops, mangrove products for construction and fuel, and fish as a protein source. Human population growth and an escalating demand for natural resources threaten estuarine critical habitats and their functioning, exacerbated by the effects of climate change. Decadal and seasonal land-use and land-cover (LULC) changes in the Ruvu Estuary in Tanzania were investigated through analysis of Landsat 5/8 and Sentinel-2 satellite images. The estuary is river-dominated and truncated near the coast during high river flow, with tidal influence extending approximately 12 km upstream during low river flow. LULC change detection targeting nine classes (water, developed, barren, forest, grasslands, cultivated, mangroves, wetlands and mudflats) showed that estuary-associated wetlands and mangroves had declined significantly over the past two decades (1995-2016) making way for developed land (growth of Bagamoyo Town), cultivated land (agricultural expansion with increasing population) and grasslands (coastal habitat changes). Seasonal LULC changes were conversion of wetlands to cultivated land after the wet season, and transformation of fallow wetlands to grasslands. The estuarine fishery relied on a small number of mainly freshwater and marine migrant species, compared to a highly diverse mix of mainly marine species in the nearby coastal fishery. The sparsity of quantitative fisheries data, spectral confusion when modelling land-cover change, and absence of household survey data to assess livelihood activities remain major information gaps. Generalized recommendations for improving socio-ecological change studies in WIO estuarine systems are provided.

Keywords: Estuarize-WIO, Ruvu Estuary, land-use/ land-cover analysis, small-scale fisheries

Introduction

Estuaries are amongst the most productive ecosystems in the world (Costanza *et al*., 1997) and have supported a range of rural to urban coastal communities throughout recorded history (Gari *et al*., 2015). In the Western Indian Ocean (WIO), over-exploitation by fast-growing human populations now threatens the ecological functioning of estuaries and the essential benefits derived from them (Hamerlynck *et al*., 2010; Barbier *et al*., 2011; papers in Diop *et al*., 2016). For example, reduced freshwater inflow because of damming or freshwater extraction in upstream catchment areas threaten critical estuarine habitats (e.g., mangroves; Friess *et al*., 2019) which in turn affects estuarine nursery function (Gillanders and Kingsford, 2002) and therefore recruitment of juvenile fish and prawns to fished populations. Local over-exploitation of goods and services in estuaries, such as harvesting of mangroves, fishing and encroachment worsen the effects of freshwater scarcity, hastening the degradation of critical habitats (Diop *et al*., 2016).

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Socio-ecological systems (SES) assessments of estuaries can be complex with a high data demand – yet the interactions between the human and natural systems cannot be ignored if estuaries are to continue to provide natural resources for livelihoods (Milner-Gulland, 2012). As a case study in a data-poor environment, a SES assessment of the Ruvu Estuary in Tanzania was undertaken. The area has been settled for millennia by a succession of civilizations (Mosha and Plevoets, 2020) and is a highly productive part of the coast that supplies local and distant markets with fish and agricultural products (Mkama *et al*., 2010). SES at the Ruvu Estuary, as elsewhere in the WIO, are dominated by fish-based farming (FBF) systems (Hamerlynck *et al*., 2020; Francisco *et al*., 2021; Furaca *et al*., 2021; Mwamlavya *et al*., 2021), in which households derive some 30 to 50 % of their income from fisheries and engage in a wide livelihood portfolio, including farming, use of mangrove products, livestock herding, bee keeping and operating small business enterprises (Hamerlynck *et al*., 2020).

Seasonal and decadal changes in land-use and land-cover (LULC) are good indicators of socio-ecological interactions, because they provide information on hydrological and ecological conditions that govern natural capital use (e.g., Ngondo *et al*., 2021; Taylor and Suthers, 2021). The aims of this study were to: assess seasonal and decadal change in LULC based on an analysis of satellite images downloaded from NASA's Landsat 5/8 and ESA's Sentinel-2 programmes; and infer the importance of estuarine fisheries in FBF systems at the Ruvu Estuary based on observational and published information. A preliminary socio-ecological change assessment of the Ruvu Estuary over the past two decades and seasonally is provided, with recommendations for future research in data-poor estuarine systems of the tropical WIO.

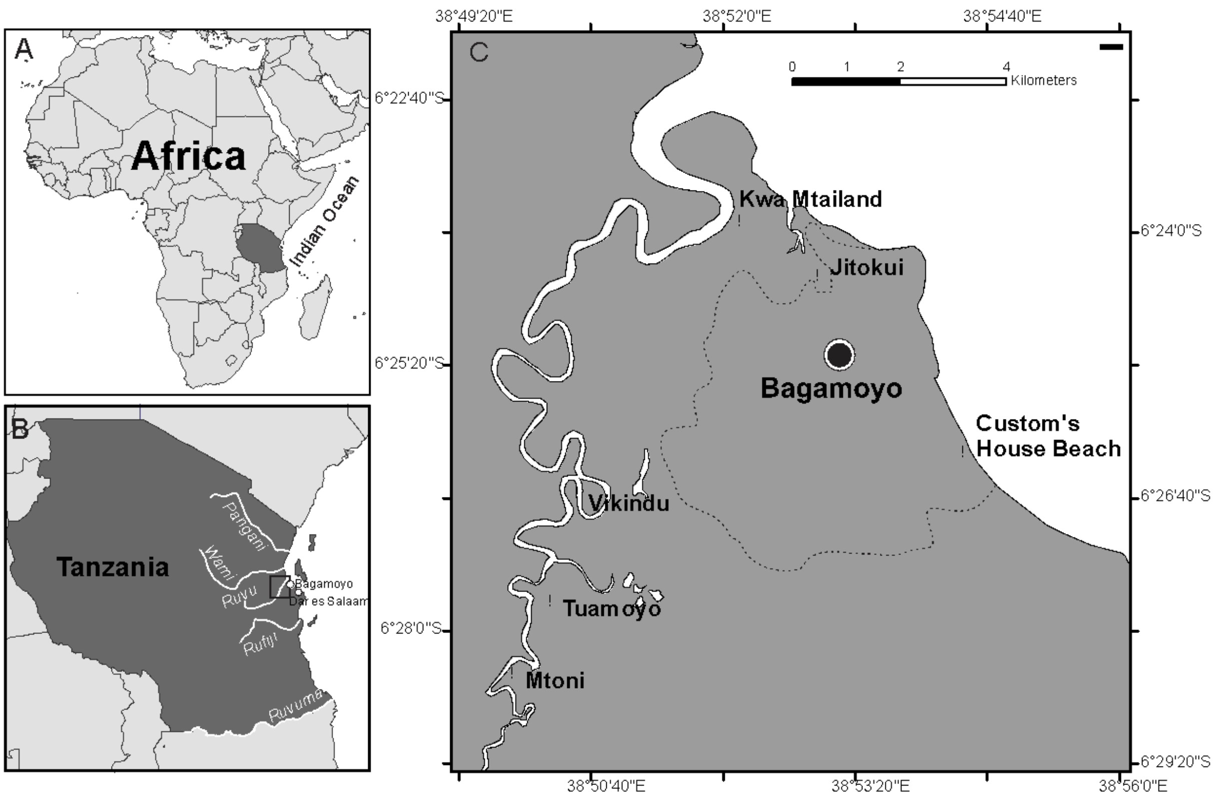

Figure 1. Location of the Ruvu Estuary study area in (A) the Western Indian Ocean and (B) relative to other major river systems and estuaries in Tanzania. In (C), fish landing sites mentioned in the text are shown.

Materials and methods

Study area

The Ruvu Estuary receives freshwater inflow from the Wami Ruvu Basin (WRB) and discharges into the WIO on the mainland side of the Zanzibar Channel, some 5 km north of the coastal town of Bagamoyo (Fig. 1). Rainfall (900 to 1300 mm p/a; GLOWS-FIU, 2014a) occurs in March-May and October-December, and direct freshwater flow into the estuary reaches a monthly maximum of 150 m^3/s at Morogoro Bridge, some 45 km upstream of the estuary mouth (GLOWS-FIU, 2014b; 2014c). Upstream of the estuary, the Ruvu River flows through major agricultural, industrial, and urban areas where freshwater is diverted for irrigation, industrial, aquaculture and domestic use (Ngondo *et al*., 2021). With rapid coastal expansion, particularly at Dar es Salaam where there is a critical water supply/demand deficit, the WRB is of high strategic importance and has been the subject of numerous impact assessments, predictive models, policy documents and published research (e.g., GLOWS-FIU, 2014a-d; van Eeden *et al*., 2016; Mdee, 2017; Alphayo and Sharma, 2018; Miraji *et al*., 2019; Ngondo *et al*., 2021). The WRB is managed by the Wami Ruvu Basin Water Office (WRBWO) of the Ministry of Water and Irrigation in Tanzania.

The area of interest (AOI) for this study was taken as the final 10 to 12 km of the Ruvu Estuary, to include the lower river, the river-estuary transition, estuary (based on upstream salinity penetration; GLOWS-FIU, 2014d), and an area of the offshore bay highly influenced by river/estuarine water during tidal exchange and floods. Eight zones within the AOI were identified according to proximity to the estuary: estuary-supporting habitats (zones 1-2); river adjacent and river influencing landscape (zone 3); urbanized land including Bagamoyo Town (zones 4 and 5); and land influenced by this urbanization to the south. Bagamoyo Town lies outside the estuarine functional zone but was included in the LULC assessment because its urban growth (built-up area and population size) was considered a major driver of socio-ecological change and anthropogenic impact on estuarine resources (summarized in Groeneveld *et al*., 2021). Zones 6-7 are less urban-influenced and span some of the land between the Ruvu and the Wami estuaries to the north, and zone 8 includes the offshore plume area off the Ruvu mouth. The study area comprised 458 km^2, of which 358 km^2 was land.

Catchment basin

Information on rainfall, river discharge, water level, geology, hydrogeology, administration, infrastructure and population demographics in the catchment area of the Ruvu River were obtained from an online 'Digital Atlas of Water Resources' (http://glows/fiu.edu). Geographically, the information originates from outside the estuarine study area, but is crucial for quantifying the variability of long term and seasonal freshwater discharge into the estuary. Spatial patterns of water supply, demand and use at the WRB hydrological station at Morogoro Road Bridge showed peak discharge in April to May with a secondary peak in November to January (GLOWS-FIU, 2014b; http://glows/fiu.edu). Multiple studies have shown a longer term decrease in flows to the coast (GLOWS-FIU, 2013; 2014a-d) and the possible impacts across ecosystems and people (Semesi *et al*., 1998; Kiwango *et al*., 2015; Shaghude, 2016; Duvail *et al*., 2017; Miraji *et al*., 2019; Macharia *et al*., 2020). The lack of environmental flow management and enforcement in the WRB influences freshwater flow into the Ruvu Estuary, as a vital component of estuarine ecology (e.g., nutrient processing, sediment trapping, maintenance of critical habitats; Kiwango *et al*., 2015) all of which are necessary to sustain livelihoods of coastal communities.

Estuary zones based on salinity profiles

Salinity is a critical variable in estuaries, which governs the distribution of biota through mixing of freshwater inflow and tidal influence at various spatio-temporal scales. Salinity gradients influence the distribution of estuarine habitats, availability of freshwater, land-cover (LC), land-use (LU) and fished resources. Defining salinity zones that correlate with biological tolerance and distribution of species throughout the estuary (some being directly targeted for subsistence by nearby communities) was the initial step. A broad-category system was adopted with oligohaline (0.5-5.0 psu), mesohaline (5.0-18.0 psu), and polyhaline (18.0 to 30.0 psu) conditions (see Montagna *et al*., 2013). Salinity measurements obtained from GLOWS-FIU (2014c) for June 2013 and TAFIRI (November 2017 and May 2018) datasets ranged between 0 psu (freshwater) and 32 psu (marine) in the estuary with well-mixed conditions throughout and across data collection times. Four salinity-based estuarine zones could be defined as: mouth/bay (20-30 psu), lower reaches (10-19 psu), middle reaches (5-9 psu) and upper reaches (0.5-4 psu).

Simple interpolation on a 2D GIS platform was used to estimate the range of salinity profiles in the upper and lower water column during low and high flow periods. The estuary was highly river-dominated during the high flow seasons, and relatively truncated with mixed salinity only at the coast (Fig. 2). The estuary extended offshore during high flow seasons (Fig. 2) creating an offshore mixing area with high fluvial settlement, unique marine habitats (mud banks), processes (e.g., Scharler *et al*., 2016) and communities (e.g.,

Figure 2. Salinity zones based on average salinity conditions (surface and bottom) across the Ruvu Estuary during high flow (Apr-May) and low flow (Jul-Sep) seasons. Salinity measurements were obtained from GLOWS-FIU (2014c) for 2013 and from field measurements taken by TAFIRI in 2017/2018.

MacKay *et al*., 2016). During low flow conditions, the salinity-based zones extended some 10 km upstream from the estuary mouth creating a significantly larger estuarine area. A larger land-based estuary will equate to greater ecological function during these times, as estuary function depends on the salinity gradient (Whitfield *et al*., 2012). Water temperature in June 2013 (low flow) ranged between 25.1 and 26.7 °C (GLOWS-FIU, 2014b), and during November 2017 and May 2018 (high flows) it ranged between 26.5 and 34.5 °C, with slightly higher temperatures on the outgoing tide. The difference was attributed to marine and fluvial influences during low and high flow periods, respectively and confirmed a strongly seasonal estuary.

Remote sensing of land use and land cover (LULC)

Satellite images of the Ruvu Estuary, including from NASA's Landsat 5/8 missions and the ESA's Sentinel-2 programme, were sourced from the USGS

Table 1. Satellite imagery sources, acquisition dates and % cloud cover in the study area.

Decadal Study				Seasonal Study			
Date	Satellite	Cloud Cover %	Season	Date	Satellite	Cloud Cover %	Season
1995-06-25	Landsat 5	0.01	Wet	2016-12-27	Sentinel-2	5.16	Dry (L)
2006-06-07	Landsat 5	1.44	Wet	2017-07-15	Sentinel-2	1.38	Wet (H)
2011-07-07	Landsat 5	0.06	Wet	2018-01-01	Sentinel-2	4.82	Dry (L)
2016-07-04	Landsat 8	0.39	Wet	2018-06-10	Sentinel-2	1.12	Wet (H)

EarthExplorer platform (https://earthexplorer.usgs.gov/). Landsat imagery was assessed (30 m resolution) to compare decadal changes from four images (<20 % cloud cover), spanning a 21-year period (1995, 2006, 2011, 2016) during wet southeast (SE) monsoon conditions (June, July) (Table 1). For the seasonal comparison, higher resolution (10 m) Sentinel-2 satellite images representative of year/month combinations (<20 % cloud cover) for the wet SE monsoon (July 2017 and June 2018) and the drier northeast (NE) monsoon seasons (December 2016 and January 2018) were used. Radiometric calibration converted digital numbers (DN) to surface reflectance values to compare different images, the Apparent Reflectance function was used for further adjustments and red, green, blue and near-infrared spectral bands were input into modelling and assessment. A land-cover classification scheme was adapted from the USGS and NOAA Coastal Change Analysis Program (C-CAP) to fit this study. The scheme was collapsed into nine LULC classes: Water, Developed, Barren, Cultivated, Forests, Mangroves, Mudflats, Wetlands and Grasslands for the decadal and seasonal assessments (Table 2), with an expanded selection of 22 classes to detect change at a higher, seasonal resolution (see adjunct to Fig. 6). Supervised classification (decadal change) and object-based imagery analysis approaches (seasonal change) were adopted using a support vector machine classifier on a GIS (ArcMap™ GIS) and the RGB and NIR bands (Red, Green, Blue and Near-Infrared). Classification of land-cover categories used the maximum likelihood classification algorithm.

Table 2. Classes used for land use/land cover change detection.

LC	Type	Description
1	Water	Coastal open water, estuarine water and plumes, rivers
2	Developed	Medium to low density housing, industry, urban mixed use
3	Barren	Coastal bare sand, exposed soil
4	Forest	Coastal, disturbed, mixed woodlands, tree cover and thickets
5	Grasslands	Natural or disturbed grasslands, herbaceous cover
6	Cultivated	Subsistence or agricultural harvested and fallow croplands, mariculture and salt pans
7	Mangroves	Dense or spare mangrove crown cover, including freshwater swamp forests
8	Wetlands	Vegetated or non-vegetated water bodies, swamps and marshes
9	Mudflats	Estuarine intertidal mudflats

Model training and validation relied on a combination of ground truth methods. Of the 365 ground truth points used, 165 were geolocated photographs and 200 were points from Google Earth™ or ESRI base map imagery (source DigitalGlobe, 0.5 m resolution). Overall classification accuracy was determined as the percentage of correctly classified samples of an error matrix (Producer and User Accuracies), and the Kappa statistic provided a statistically valid assessment of the classification quality. A Kappa value > 50 % was considered satisfactory for modelling land use change (Pontius, 2000).

To illustrate the relationship between LULC categories and the percentage coverage in each AOI zone during the selected seasons, a distance-based redundancy analysis (dbRDA) was conducted. The ordination was constrained by the best-fit explanatory variables from a multivariate multiple regression analysis (DISTLM) with vector overlays for predictors explaining significant proportions of the variation.

Fish and shellfish resources

The species of fish and shellfish caught with bottom-set nets and landed at four sites in the channels of the Ruvu Estuary were identified during field sampling undertaken by TAFIRI between November 2017 and March 2018. A standard field guide (Anam and Mostarda, 2012) was used to aid species identification. The Kwa Mtailand and Jitokui sites were in the lower estuary (mostly poly- and mesohaline conditions) and the Vikundu and Mtoni sites were in the upper estuary and river-estuary transition (meso- and oligohaline) (Fig. 1; Fig 2). Fish species present at the Customs House fish market in Bagamoyo Town were photographed using a cell-phone camera and identified from the photographs. Because market samples were mixed, the origin of identified species (estuary channels, bay, offshore marine) could not be discerned. Additional information on species present in the estuary was obtained from reports by Yona (2017) and GLOWS-FIU (2014c).

The observed species were categorized into estuarine-use functional groups after Elliott *et al.* (2007). Five groups were defined: freshwater stragglers comprising of freshwater species found in low numbers in estuaries and whose distribution is limited to the low salinity upper reaches of estuaries; freshwater migrants found regularly and in moderate numbers in estuaries, extending beyond the oligohaline sections; estuarine species, including estuarine residents and migrants; marine migrants including species that spawn at sea and enter estuaries in large numbers, mainly as juveniles, and including marine-estuarine dependent and opportunist species; and marine stragglers that spawn at sea and only enter estuaries in low numbers in areas where salinities are high (Harrison and Whitfield, 2008). Adult habitats, feeding ecology and mean trophic level (± SE) based on food items were obtained from Fishbase (https://www.fishbase.se).

Results and Discussion

Decadal land cover change based on Landsat 5/8 imagery (1995 – 2016)

Landsat imagery showed a significant decline in estuary-associated wetlands from 42 % of the AOI in 1995 to 17 % in 2016 (Fig. 3). The similarity of water area coverage across all temporal comparisons (20 – 23 % of the

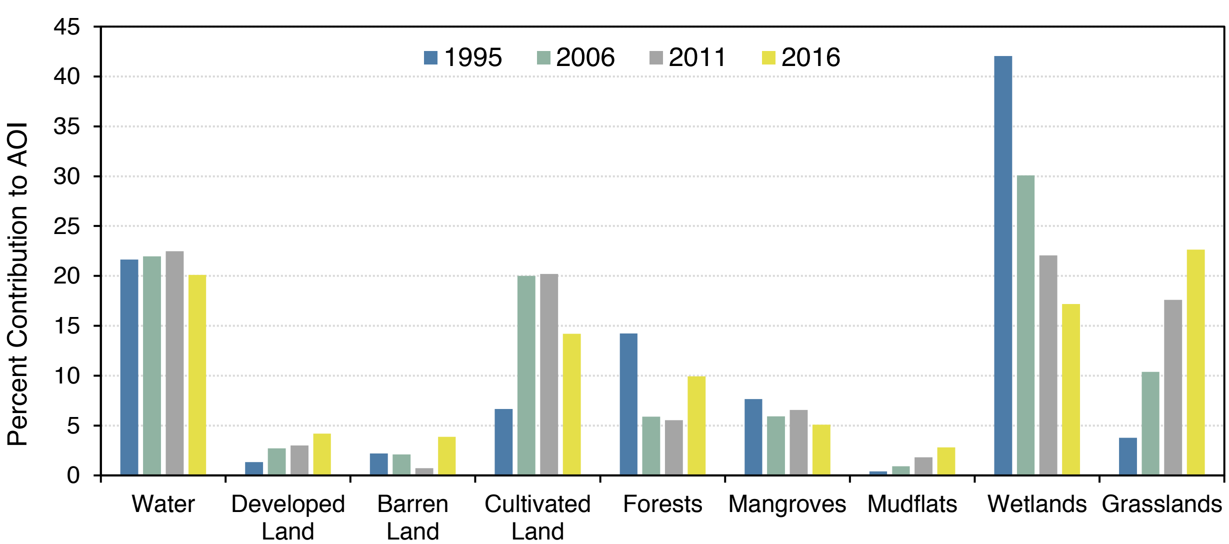

Figure 3. Historical changes (interdecadal) in LC around the Ruvu Estuary. Percent cover across nine categories related to estuary, estuary supporting habitats and developed land.

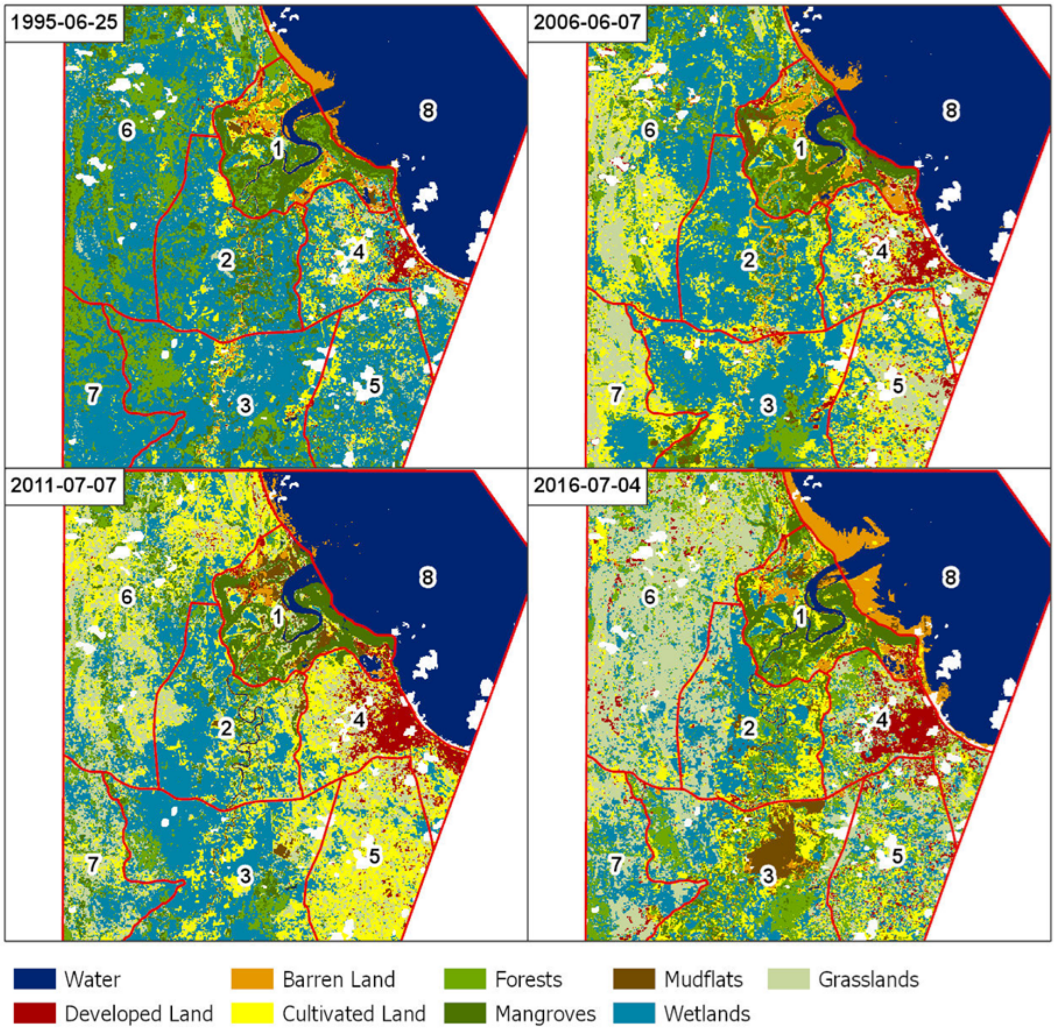

Figure 4. Historical changes in land use/land cover around the Ruvu Estuary based on an analysis of Landsat 5/8 satellite images for the period 1995-2016.

AOI) confirmed that studied periods had similar hydrological characteristics (Fig. 3). Mangrove-cover declined from 8 % to 5 % of the AOI in contrast to other LC classes. Linear increases were found in grasslands (4 % to 23 %), developed land (1 % to 4 %) and mudflats (<1 % to 3 %). Cultivated land (7 % to 14 %) and forested land (14 % to 10 %) showed variable levels of change between 1995 and 2016, but with overall expansion of these classes. Overall, the significant changes since 1995 have been the increase in developed land (reflecting the growth of Bagamoyo Town), cultivation (reflecting agricultural expansion with increasing population) and grasslands (coastal habitat changes with changing land use activities) at the expense of wetlands. Noting however, that 2016 was the driest rainfall year of the change assessment and possibly over-emphasized grassland expansion.

The model assessment performance was moderately high (0.74, Kappa of 0.70). Model performance (Producer's Accuracy) showed 97 % reliability of developed land prediction and good predictability of grasslands (84 %), forests (80 %) and cultivated land (70 %). Only 28 % of mudflat areas were modelled correctly and with similar spectral signatures to pans for salt production and mariculture. The User's Accuracy showed a good reliability of the classes selected, with water, barren land, grasslands, wetlands and forests classified correctly >80 % of the time. Least accurate were mudflats (45 % agreement), being confused with cultivated land.

The remotely sensed LULC trends reflected long term change around the Ruvu Estuary and were related directly or indirectly to the expansion of Bagamoyo Town over the past 21 years (Fig. 4). The spectral confusion amongst some classes (interchangeable cultivated- and wetland spectral signatures next to the estuary and mangroves and forests having similar

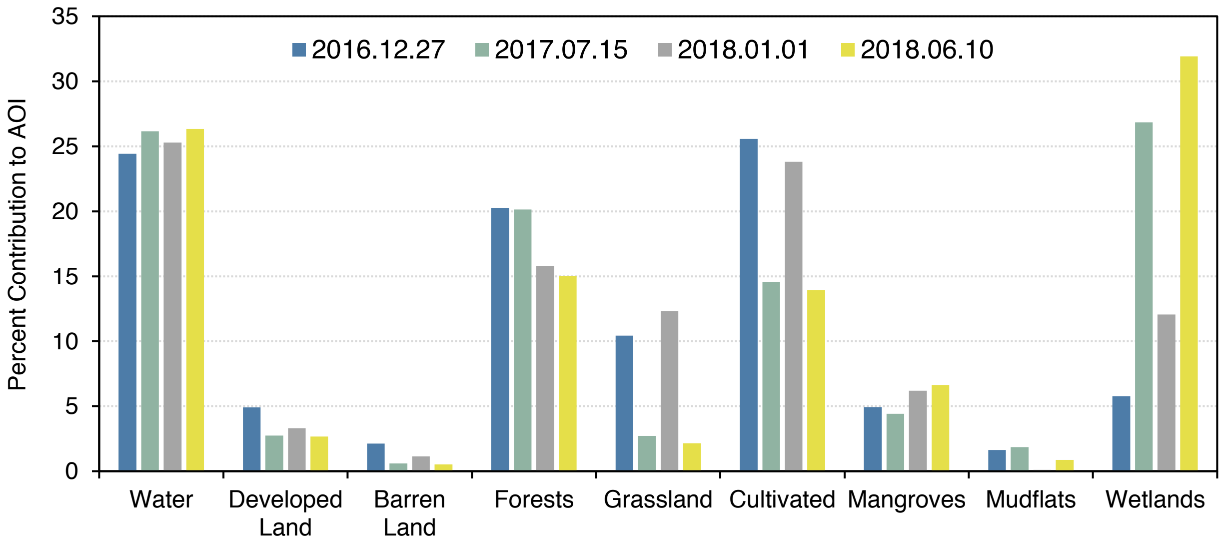

Figure 5. Seasonal LC change around the Ruvu Estuary from four alternating dry/wet timestamps (2016-2018). Percent cover across nine categories related to estuary, or estuary supporting, habitats.

spectral signatures) were mostly well resolved through rule-based selection procedures (such as proximity to the estuary). Cultivation is the main land use activity in this coastal area of the WRB, with main crops of maize, rice, cassava, cashew, sisal, vegetables, and citrus. Cultivation directly affects water quality flowing into the estuary with high turbidity throughout the year, and high nutrients (NO_3, NH_4, SRP and TP) emanating from fertilizer-contaminated return flows (Ngoye and Machiwa, 2004).

Seasonal land cover change based on Sentinel-2 imagery (2016-2018)

Seasonality was evident in LULC change detection analyses. Water (24 – 26 %), cultivated land (14 – 26 %), forests (15 – 20 %) and wetlands (6 – 32 %) dominated land cover in the AOI during the four time periods (Fig. 5). Seasonal changes in wetlands, cultivated land and grasslands were most pronounced. Wetlands decreased notably during the dry season, as cultivation increased, and grassland areas spread through drier terrains. Water area coverage increased marginally during the wet season, but forests, mangroves and mudflats showed no seasonal trends from these data. In 2016, developed land covered a similar proportion of the AOI (4.9 %) to the Landsat analysis (4.2 %), providing some confidence in the compatibility of decadal and seasonal models.

The analysis supported a broad seasonal pattern, with wetlands being converted to cultivated areas during the dry season, and uncultivated wetlands becoming grasslands (Fig. 6). However, the estimates of seasonal change in land cover were affected by mosaics of pixels that could alternatively be attributed to wetlands, grasslands or mudflats, caused by classification confusion from similar spectral signatures. Cultivated land next to the estuary differed substantially from cultivated land further away (e.g., between developed land parcels), attributed to differing agricultural activities. The model did not satisfactorily distinguish between mudflats, non-vegetated wetlands, grasslands and cultivated land during the dry season. Distinguishing between cultivated land, wetlands, forests and mangroves was also challenging during the wet season. Despite land-cover classification inconsistencies in the model, there was a moderately high assessment performance of 76 % (Kappa of 0.72). Producer's Accuracy showed good performance of classification of water (89 % accurate), forests (86 %), cultivated land (83 %) and developed land (82 %). Worst performing classifications were of grasslands (40 %) and mudflats (44 % modelled correctly). Class reliability (User's Accuracy) indicated excellent to moderately good results with water and barren land classes showing excellent results (>95 %) and wetlands and forests having >80 % accuracy. Remaining land classes had reliability of 60 – 70 %.

Linear modelling of spatio-temporal changes incorporating seasonality across all AOI zones showed that zone 1 (estuary) is a unique land-cover functional area dominated by mangroves (Fig. 7). Mangroves are an important resource (wood) and ecological support service (nursery area) (Semesi *et al.*, 1998) but their extent is threatened by freshwater deficits and concomitant saltwater intrusion. Of the seven mangrove species

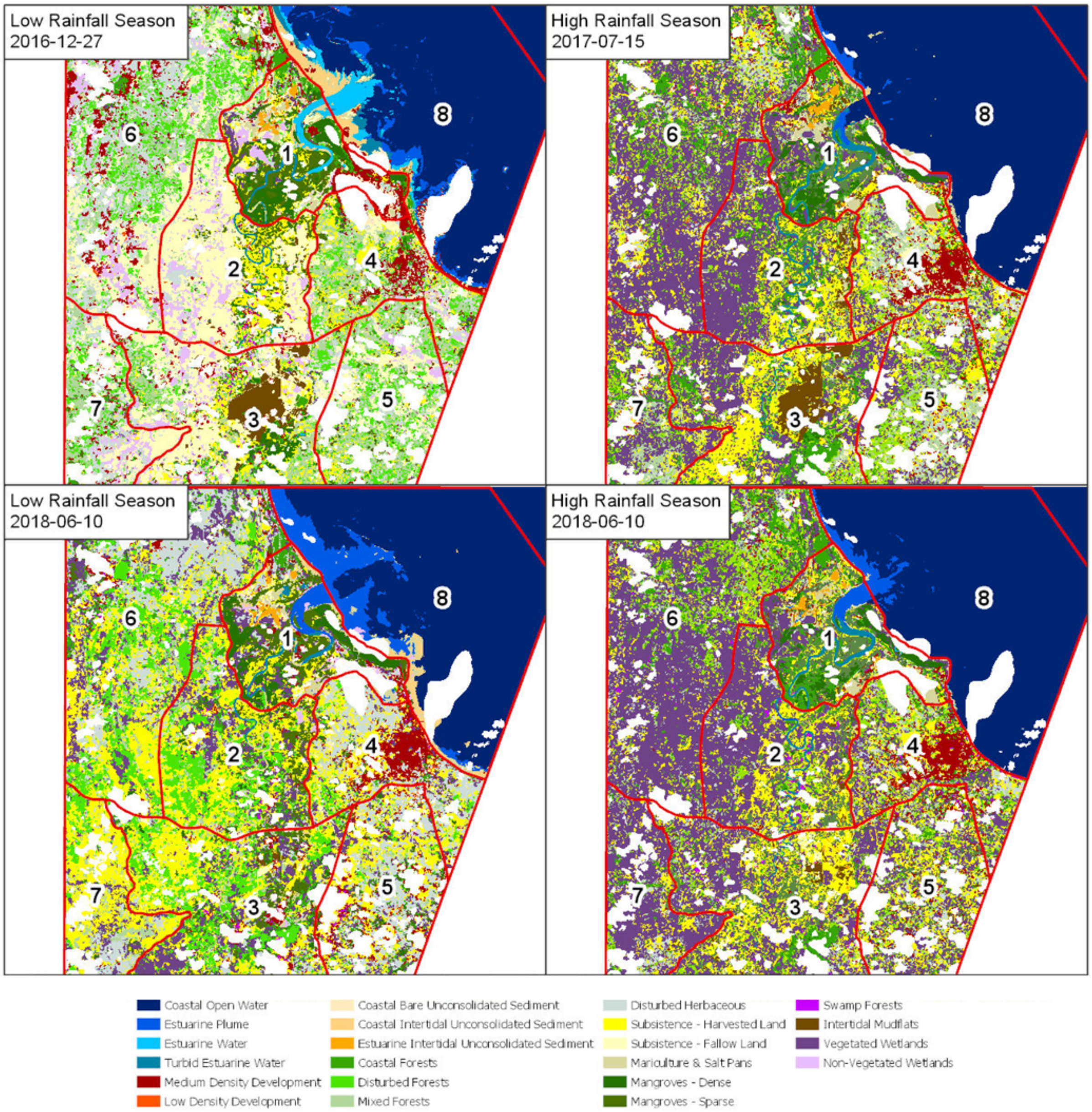

Figure 6. Seasonal land use/land cover assessment around the Ruvu Estuary, based on a comparison of Sentinel-2 satellite images of wet (SE monsoon) and dry (NE monsoon) seasons in 2016-2018. The expanded selection of 22 land cover classes to detect change at a higher, seasonal resolution is shown.

represented in the Ruvu, only two (*Sonneratia alba* and *Rhizophora mucronata*) have a high relative salinity tolerance, all other species being medium-to low tolerant (GLOWS-FIU, 2014c). The upper estuary and estuary-river transition (zones 2 and 3) are highly seasonal, with LULC changes alternating between wetlands and cultivated lands. The zones with expanding development (zones 4 and 5) show fewer seasonal signals, as development has a 'harder' permanent footprint precluding other land uses. In patchy mosaics between developed areas, cultivated (including salt and mariculture pans) and grassland areas are expanding at the expense of previous wetland areas.

Historical and seasonal trends for the main LULC classes in seven zones (excluding zone 8) are summarised in Table 3. There are critical declines in wetlands in all zones since the 1990s, with increasing cultivation in most zones (except zones 1 and 7). These overall findings agree with a larger LULC study of the WRB (Ngondo *et al.*, 2021) and are related to water resource implications. Since 1990, coastal populations have increased significantly with related demands for agricultural products and water, resulting in the conversion of wetlands to cultivated lands. Significant changes to freshwater flow was also recognized in response to potable and agri-sector demands.

Table 3. Summary of land use/land cover spatio-temporal change around the Ruvu Estuary. Changes depicted as increasing (↑) or decreasing (↓) trends. Trends in estuary or estuary-associated habitats shown in bold.

AOI ZONE	1	2	3	4	5	6	7
Area size (km^2)	36.10	47.59	68.07	34.81	45.31	97.93	27.93
Mean Elevation (m)	6.65	4.13	12.37	4.54	14.24	2.43	1.68
Mean Slope ()	2.71	1.89	2.32	2.76	3.08	2.72	2.64
Main Land Cover Classes	Mangroves Cultivation	Cultivation Wetlands	Cultivation Wetlands Forests	Forests Cultivation Developed Grasslands	Forests Cultivation Wetlands Grasslands	Wetlands Forests Grasslands Cultivation	Wetlands Forests Cultivation
Historical Trend	Forests↓ **Wetlands↓** Grasslands↑	**Wetlands↓ Mangroves↓** Cultivation↑	Forests↓ **Wetlands↓** Cultivation↑	Developed↑ Grasslands↑ **Wetlands↓**	Cultivation↑ **Wetlands↓**	Cultivation↑ Grasslands↑ **Wetlands↓**	**Wetlands↓**
Ave. Seasonal Trend (wet to dry)	**Mangroves↑** Cultivation↑ Forests↓	Cultivation↑ **Wetlands↓**	Cultivation↑ **Wetlands↓**	Cultivation↑ **Wetlands↓**	Cultivation↑ **Wetlands↓**	Grasslands↑ Cultivation↑ **Wetlands↓**	Grasslands↑ Cultivation↑ **Wetlands↓**

Flows are set to further decline with changes in climate, especially at the coast where rainfall has decreased since 1990 (Ngondo *et al*., 2021).

Fish and shellfish resources

A total of 77 fish and shellfish species were identified, of which 82 % were bony fishes and 10 % were crustaceans (Appendix 1). The remaining 8 % included three ray species, two cephalopods and a sea cucumber. The best represented fish families, by number of species observed, were carangids (Carangidae, 6 spp), snappers (Lutjanidae, 5), emperors (Lethrinidae, 4), and three species each of anchovies (Engraulidae), ponyfishes (Leiognathidae), parrot fishes (Scaridae) and mackerels and tunas (Scombridae). Wrasses, rabbitfish, catfish, mullet, croaker, goatfish, grouper and barracuda were also present. Crustaceans comprised of five penaeid prawn species (Penaeidae) common in WIO coastal areas (i.e., *Fenneropenaeus indicus*, *Metapenaeus monoceros*, *Penaeus monodon*, *P. japonicus* and *P. semisulcatus*), mangrove crab *Scylla serrata* (Portunidae), spiny lobster *Panulirus ornatus* (Palinuridae) and the invasive giant freshwater prawn *Macrobrachium rosenbergii* (Palaemonidae) (Kuguru *et al*., 2019). The species list included freshwater, brackish and marine species of which several were anadromous (e.g., marine species that utilize estuaries as nursery areas). The final species list (Appendix 1) did not fully represent all the taxa present in the Ruvu Estuary and surrounding coastal areas because sampling routines were selective for species with higher commercial value and cryptic or uncommon species could not be identified. Shortcomings of the present species list are highlighted when compared with a more comprehensive list compiled by Yona (2017) for estuarine (Ruvu) and non-estuarine mangroves (Bagamoyo).

Monitoring fish zonation and guilds against a reference situation is a useful tool to measure the impact of human or other disturbance on the structure of fish communities, as an indicator of ecological integrity (Aarts and Nienhuis, 2003; Harrison and Whitfield,

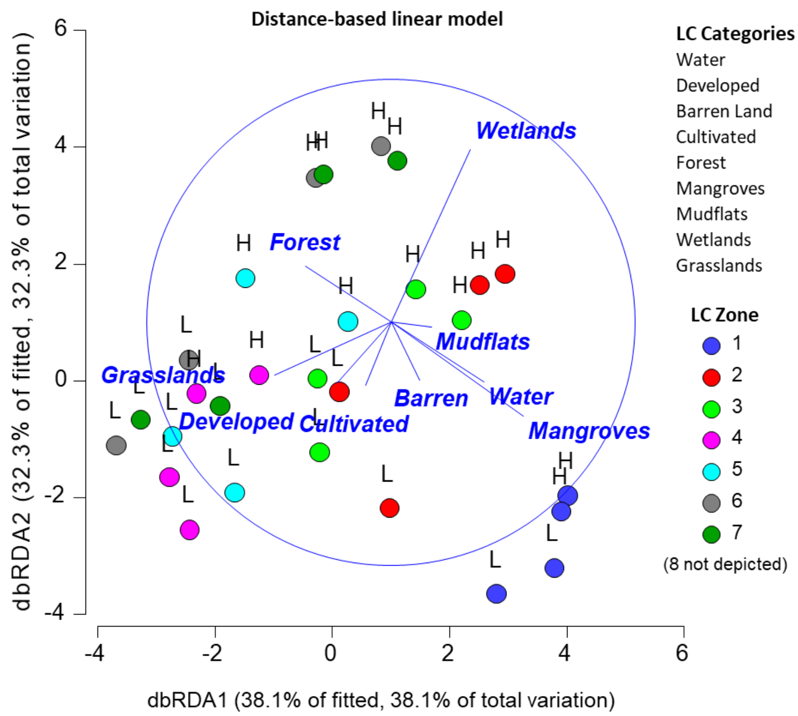

Figure 7. Distance based linear model of Ruvu Estuary land use/land cover assessments according to estuary zones (AOI zone 1-7), wet (high flow – H) and dry (low flow – L) seasons and across nine land cover classes. Axes dbRDA1 and 2 account for 70.4 % of variation.

2008). Nine species were recorded in dry-season samples obtained from fishers operating with bottom-set nets within the channels of the Ruvu Estuary. All were either benthopelagic or demersal species, consistent with the gear used. Three species were present in samples in both zone 1 (lower estuary with poly- and mesohaline conditions of 10-30 psu) and zone 2 (upper estuary with meso- and oligohaline conditions of 0.5-9 psu); African sea catfish *Arius africanus*, giant freshwater prawn *M. rosenbergii* and sharptooth croaker *Otolithes ruber* (Table 4). *Arius africanus* and *M. rosenbergii* are both freshwater migrants that are found regularly and in substantial numbers in estuaries, and in the case of *A. africanus*, also in marine waters along the coast. *M. rosenbergii* requires estuarine conditions to complete its life cycle and sustain viable populations. *O. ruber* is an amphidromous marine migrant, which regularly migrates between freshwater and the sea (in both directions) but not for the purpose of breeding.

Three species were present in zone 1 only, the marine migrants grey mullet (*Mugil cephalus*) and tiger prawn (*P. monodon*), and the honeycomb stingray (*Hymantura uarnak)*, a marine straggler. Two species present in zone 2 only were freshwater stragglers, sharptooth catfish (*Clarias gariepinus*) and tilapia (*Oreochromis esculentus*). A third species present only in zone 2 was darkfin eel catfish (*Plotosus limbatus*), categorized as an estuarine species that undertakes migrations to marine and freshwater areas. For all nine species, capture locations within the estuary corresponded well with their estuary-associated guilds obtained from the literature (Harrison and Whitfield, 2008; https://www.fishbase.se).

Based on food items (detritus, plankton, plant and algal material, small crustaceans and fish) all nine species occupied mid to lower levels in estuarine foodwebs, with trophic values ranging from 2.5 ± 0.2 (detritivores) to 3.9 ± 0.6 (omnivorous bottom feeders or smaller piscivores) (Table 4). Species observations were however constrained by sampling of a single gear type (bottom-set nets), and therefore conclusions could not be drawn on species selected by other gear types, such as gillnets or seine nets. In particular, small pelagic fishes were absent from samples taken in the Ruvu Estuary, in direct contrast with several other WIO estuaries where they made up the bulk of landings (Mugabe *et al*., 2021; Manyenze *et al*., 2021).

Based on the available data, the estuarine fishery in the Ruvu relies on few species and is not as important to local communities as the nearshore coastal fishery,

Table 4. Estuarine use functional groups (after Elliot *et al.*, 2007 and Harrison and Whitfield, 2008) of species observed in catches made by bottom-set nets in the channel of the Ruvu Estuary. Zone 1 refers to the Kwa Mtailand and Jitokui landing sites (lower estuary) and Zone 2 to the Vikundu and Mtoni sites (upper estuary and river-estuary transition). Adult habitat, feeding ecology, mean trophic level (± SE) and vulnerability obtained from https://www.fishbase.se.

Estuarine functional group	Common name	Species	Family	Zone 1	Zone 2	Adult habitat	Feeding ecology	Trophic level
Freshwater straggler	African sharptooth catfish	*Clarias gariepinus*	Claridae		1	Benthopelagic	Omnivorous bottom-feeder	3.8 ± 0.4
Freshwater straggler	Sigida tilapia	*Oreochromis esculentus*	Cichlidae		1	Benthopelagic	Planktivorous	2.5 ± 0.2
Freshwater migrant	African sea catfish	*Arius africanus*	Ariidae	1	1	Benthopelagic	Omnivorous bottom-feeder	3.8 ± 0.6
Freshwater migrant	Giant freshwater prawn	*Macrobrachium rosenbergii*	Palaemonidae	1	1	Demersal	Omnivorous bottom feeder	3.4
Estuarine species	Darkfin eel catfish	*Plotosus limbatus*	Plotosidae		1	Demersal	Piscivorous	3.9 ± 0.6
Marine migrant	Flathead grey mullet	*Mugil cephalus*	Mugilidae	1		Benthopelagic	Detritivorous	2.5 ± 0.2
Marine migrant	Giant tiger prawn	*Penaeus monodon*	Penaeidae	1		Demersal	Detritivorous	3.4
Marine migrant	Tigertooth croaker	*Otolithes ruber*	Sciaenidae	1	1	Benthopelagic	Piscivorous	3.6 ± 0.6
Marine straggler	Honeycomb stingray	*Hymantura uarnak*	Dasyatidae	1		Demersal	Piscivorous	3.6 ± 0.6

which relies on multiple gear types and habitats to capture a rich mix of species landed at Bagamoyo. Freshwater dominance of the Ruvu Estuary during a large part of the year, and a resulting truncated estuary with fewer habitats than at larger marine-dominated estuaries in the WIO, can plausibly explain the reliance of estuarine fishers on a few species.

Conclusion and recommendations

The Ruvu Estuary is strongly seasonal and river-dominated during high river flow periods, when it becomes longitudinally truncated with mixed salinity only at the coast. Tidal influence extended some 10 km upstream during low river flow, creating a larger estuarine area. Modelling of land-cover change, although moderately affected by spectral confusion, showed significant declines in estuary-associated wetlands and mangroves between 1995 and 2016, with concomitant expansion of grasslands, cultivated and developed land. Wetlands are converted to cultivation during the dry season, and when uncultivated, wetlands become grasslands. The estuarine fishery relied mainly on freshwater and marine migrants, compared to a highly diverse species mix landed by a coastal fishery at Bagamoyo Town. Within the context of a socio-ecological study of the Ruvu Estuary, the absence of quantitative data on fisheries landings by species, gear type, season and georeferenced location remain major information gaps. Household surveys to determine livelihood activities and their reliance on estuarine resources are a key component of socio-ecological studies, but data were not available to address this aspect in the present study. For example, important aspects to clarify would be whether estuarine fish catches are marketed or used for home consumption; and how widespread opportunistic fishing for high-value invasive freshwater prawns is within the estuary.

Estuarine extent is a first step towards determining the freshwater needs of estuaries, which have been mostly overlooked in the WIO region (Kiwango *et al.*, 2015). To improve studies of estuaries and their associated socio-ecological systems, it is recommended that: (1) short periods of continuous monitoring of estuarine flow is undertaken, to obtain the full range of physico-chemical conditions across seasons; (2) a LULC classification system suited to complex tropical socio-ecological systems is developed, to reduce spectral confusion and increase modelling accuracy; (3) random sampling of fish landings in estuaries are undertaken to determine spatio-temporal variability; and (4) that household surveys of livelihood dependence on estuarine goods and services are required for constructing fully integrated socio-ecological change assessments.

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Appendix

Fish and shellfish species observed during field sampling at the Customs House beach landing site in Bagamoyo (Zone 8), lower estuary (Zone 1; Kwa Mtailand and Jitokui) and upper estuary and river-estuary transition (Zone 2; Vikindu and Mtoni). Bagamoyo samples represented presence/absence only.

			Location observed			
Family	**Species**	**Bagamoyo**	**Kwa Mtailand**	**Jitokui**	**Vikindu**	**Mtoni**
Acanthuridae	*Acanthurus xanthopterus*	1				
Apogonidae	*Apogon* sp	1				
Ariidae	Arius africanus	1	13	34	20	14
Atherionidae	*Atherion africanus*	1				
Belonidae	*Tylosurus crocodilus*	1				
Carangidae	*Atule mate*	1				
Carangidae	*Carangoides ferdau*	1				
Carangidae	*Caranx heberi*	1				
Carangidae	*Caranx ignobilis*	1				
Carangidae	*Coryphaena equiselis*	1				
Carangidae	*Decapterus sp*	1				
Cichlidae	*Oreochromis esculentus*				4	
Clariidae	*Clarias gariepinus*				23	27
Clupeidae	*Hilsa kelee*	1				
Congridae	*Conger cinereus*	1				
Dasyatidae	*Himantura gerrardi*	1				
Dasyatidae	*Himantura uarnak*	1		1		
Dasyatidae	*Taeniura lymna*	1				
Elopidae	*Elops machnata*	1				
Engraulidae	*Stolephorus indicus*	1				
Engraulidae	*Thryssa setirostris*	1				
Engraulidae	*Thryssa vitrirostris*	1				
Fistulariidae	*Fistularia commersonnii*	1				
Gerreidae	*Gerres filamentosus*	1				
Gerreidae	*Gerres oyena*	1				
Haemulidae	*Pomadasys kaakan*	1				
Haemulidae	*Pomadasys maculatus*	1				
Hemiramphidae	*Hemiramphus far*	1				
Holothuriidae	*Holothuria scabra*	1				
Leiognathidae	*Leiognathus equulus*	1				
Leiognathidae	*Leiognathus leuciscus*	1				
Leiognathidae	*Secutor incidiator*	1				
Lethrinidae	*Lethrinus harak*	1				
Lethrinidae	*Lethrinus lentjan*	1				
Lethrinidae	*Lethrinus microdon*	1				
Lethrinidae	*Lethrinus rubrioperculatus*	1				

		Location observed				
Family	**Species**	**Bagamoyo**	**Kwa Mtailand**	**Jitokui**	**Vikindu**	**Mtoni**
Lobotidae	*Lobotes surinamensis*	1				
Loliginidae	*Uroteuthis duvaucelli*	1				
Lutjanidae	*Aprion virescens*	1				
Lutjanidae	*Lutjanus argentimaculatus*	1				
Lutjanidae	*Lutjanus lutjanus*	1				
Lutjanidae	*Lutjanus sanguineus*	1				
Lutjanidae	*Lutjanus sebae*	1				
Mugilidae	*Mugil cephalus*			3		
Mullidae	*Upeneus taeniopterus*	1				
Mullidae	Upeneus tragula	1				
Octopodidae	*Octopus vulgaris*	1				
Ostraciidae	*Lactoria cornuta*	1				
Palaemonidae	*Macrobrachium rosenbergii*		46	1	227	
Palinuridae	*Panulirus ornatus*	1				
Penaeidae	*Fenneropenaeus indicus*	1				
Penaeidae	*Metapenaeus monoceros*	1				
Penaeidae	*Penaeus japonicus*	1				
Penaeidae	*Penaeus monodon*	1		78		
Penaeidae	*Penaeus semisulcatus*	1				
Plotosidae	*Plotosus limbatus*				18	9
Portunidae	*Scylla serrata*	1				
Psettodidae	*Psettodes erumei*	1				
Scaridae	*Leptoscarus vaigiensis*	1				
Scaridae	*Scarus ghobban*	1				
Scaridae	*Scarus rubroviolaceus*	1				
Sciaenidae	*Johnius dussumieri*	1				
Sciaenidae	*Otolithes ruber*	1	41	24	26	
Scombridae	*Auxis thazard*	1				
Scombridae	*Scomberoides commersonnianus*	1				
Scombridae	*Scomberomorus commerson*	1				
Serranidae	*Epinephelus lanceolatus*	1				
Serranidae	*Epinephelus malabaricus*	1				
Siganidae	*Siganus sutor*	1				
Silliganidae	*Sillago sihama*	1				
Sparidae	*Rhabdosargus thorpei*	1				
Sphyraenidae	*Sphyraena baracuda*	1				
Sphyraenidae	*Sphyraena jello*	1				
Synodontidae	*Saurida tumbil*	1				
Terapontidae	*Pelates quadrilineatus*	1				
Terapontidae	*Terapon jarbua*	1				
Trichiuridae	*Trichiurus lepturus*	1				